

Very long storage times and evaporative cooling of cesium atoms in a quasi-electrostatic dipole trap

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We have trapped cesium atoms over many minutes in the focus of a CO₂-laser beam employing an extremely simple laser system. Collisional properties of the unpolarized atoms in their electronic ground state are investigated. Inelastic binary collisions changing the hyperfine state lead to trap loss which is quantitatively analyzed. Elastic collisions result in evaporative cooling of the trapped gas from 25 μ K to 10 μ K over a time scale of about 150 s.

The focus of a CO₂-laser beam constitutes an almost perfect realization of a conservative trapping potential for neutral atoms [1,2]. Atoms are confined in all three spatial dimensions by the optical dipole force pointing towards the maximum of the intensity [3]. The CO₂-laser wavelength of 10.6 μ m is far below any optical transitions from the ground state which has important consequences. As one consequence, the optical potential becomes quasi-electrostatic, i.e. the static polarizability of the particle determines the depth of the trap (*quasi-electrostatic trap*, QUEST). Therefore, different atomic species [4] and even molecules [5] can be confined in the same trap. All sub-states of the electronic ground state experience the same trapping potential in contrast to magnetic traps. Atoms can thus be trapped in their absolute energetic ground state which excludes loss through inelastic binary collisions. Another consequence of the large laser detuning from resonance is the negligibly small photon scattering rate so that heating by the photon momentum recoil does not occur.

In this Rapid Communication we show that storage times of many minutes can be achieved in a focused-beam dipole trap with a low-cost, easy-to-use CO₂ laser usually employed for cutting and engraving of materials. The laser possesses neither frequency stabilization nor longitudinal mode selection. Despite the simplicity of the laser system, laser-noise induced heating rates, as first identified by Savard *et al.* [6], are found to be below 100 nK/s. Comparable storage times in a QUEST have recently been realized by O'Hara *et al.*, who utilized an ultrastable, custom-made CO₂ laser [7]. The simplicity

of our trap setup in combination with the long storage times are ideal prerequisites for experiments on interesting collisional properties of the trapped gas. As one application of the trap, we have studied hyperfine-changing collisions of unpolarized cesium atoms. As another important application, evaporative cooling of the trapped gas is demonstrated, which has so far only once been observed in an optical dipole trap [8].

The trapping potential of a CO₂-laser beam with a spatial intensity distribution $I(\mathbf{r})$ is given by $U(\mathbf{r}) = \alpha_{\text{stat}} I(\mathbf{r}) / 2\epsilon_0 c$ where α_{stat} denotes the static polarizability of the atoms [1,3]. For a focused beam of power P and waist w one gets a trap potential with a depth $U_0 = \alpha_{\text{stat}} I_0 / \epsilon_0 c$ with $I_0 = 2P/\pi w^2$. The CO₂ laser (Synrad 48-2WS) provides 25 W of power in a nearly TEM₀₀ transversal mode characterized by $M^2 = 1.2$. The laser beam is first expanded to a waist of 11 mm by a telescope, and then focused into the vacuum chamber by a lens of 254 mm focal length. The focus has a waist of 110 μ m and a Rayleigh range z_R of 2.4 mm, yielding a trap depth 120 μ K (in units of the Boltzmann constant k_B). Gravity lowers the potential height along the vertical direction to 92 μ K. The axial and radial oscillation frequencies in the harmonic approximation are given by $\omega_z = (2U_0/mz_R^2)^{1/2}$ and $\omega_r = (4U_0/mw^2)^{1/2}$ with m denoting the cesium mass. For our experimental values one gets an axial oscillation frequency $\omega_z/2\pi = 8.1$ Hz and a radial frequency $\omega_r/2\pi = 254$ Hz.

Atoms are transferred into the dipole trap from a magneto-optical trap (MOT) containing about 10^6 atoms. The MOT is loaded from an atomic beam which is Zeeman-slowed in the fringe fields of the MOT magnetic quadrupole field. The main vacuum chamber at a background pressure of about 2×10^{-11} mbar is connected to the oven chamber by a tube which is divided into differentially-pumped sections to assure a sufficiently large pressure gradient. To optimize transfer from the MOT into the dipole trap, the atoms are further cooled and compressed by decreasing the detuning of the MOT trapping laser from initially -2Γ (natural linewidth $\Gamma/2\pi = 5.3$ MHz) to -20Γ with respect to the $6^2S_{1/2}(F=4) - 6^2P_{3/2}(F=5)$ transition of the cesium D2 line. After 40 ms of compression, the distribution of atoms in the MOT has a rms radius of 120 μ m corresponding to an mean density of 10^{10} atoms/cm³. The temperature is 25 μ K as measured by ballistic expansion of the cloud after release from the MOT. After the laser beams and the magnetic field of the MOT were turned off, the atoms are trapped in the focus of the CO₂ laser

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beam which was present during the whole loading phase. Atoms are prepared in either the $F = 3$ or the $F = 4$ cesium hyperfine ground state by shuttering the MOT trapping laser 1 ms after or before the MOT repumping laser has been shuttered, respectively.

The number and spatial distribution of atoms trapped in the optical dipole trap are measured by taking an absorption image of the trapped atoms. A weak, resonant probe beam of $1 \mu\text{W}/\text{cm}^2$ intensity is pulsed for $100 \mu\text{s}$ and absorption of the atomic cloud is imaged onto a CCD camera. Fig. 1(a) shows a typical absorption image of atoms trapped in the QUEST. The image is taken 5 s after transfer from the MOT. The transmitted intensity I_t of the probe laser through the atomic sample is described by $I_t(x, y) = I_0 \exp(-A \eta(x, y))$ where I_0 denotes the laser intensity and A the absorption cross section for the resonant transition. The column density η is given by the integral of the density distribution $n(x, y, z)$ along the direction of the laser beam.

By fitting a thermal equilibrium distribution [9] to the data, we derive the mean density \bar{n} , the total number of trapped atoms N and the temperature T . The maximum absorption of the trapped cloud is typically 17 % in the center of the distribution yielding a mean density of $4 \times 10^9 \text{ atoms}/\text{cm}^3$ in the dipole trap. The atoms have axially expanded into an rms extension of $750 \mu\text{m}$ while the radial rms extension is $30 \mu\text{m}$. The temperature is the same as in the MOT before transfer indicating that the atoms are cooled into the dipole trap by the MOT.

Typically 10^5 atoms are transferred into the dipole trap. Assuming sufficient ergodicity, the number of atoms transferred from the MOT into the dipole trap can be determined from the phase-space integral $\int f_{\text{MOT}}(\mathbf{x}, \mathbf{p}) \theta(U_0 - \epsilon) d\mathbf{x} d\mathbf{p}$ which describes the projection of the phase-space distribution $f_{\text{MOT}}(\mathbf{x}, \mathbf{p})$ in the MOT onto the trapping region of the dipole trap. The Heavyside step function $\theta(U_0 - \epsilon)$ equals 1 when the total energy $\epsilon = U(\mathbf{r}) + p^2/2m$ of atoms in the dipole trap is smaller than the trap depth, and 0 elsewhere. Taking our experimental parameters, one expects 2×10^5 atoms to be transferred into the dipole trap in reasonable agreement with the actual value.

To measure the radial oscillation frequency of atoms in the dipole trap, we take advantage of the fast switching capability of the CO_2 laser. The laser can be turned off within about $200 \mu\text{s}$ by simply switching the RF power supply driving the gas discharge. By turning the laser off for a short time interval (around 1 ms), the trapped ensemble moves ballistically until the laser is turned on again (*release-recapture*). Part of the atoms will have escaped from the trap, while the recaptured atoms constitute a non-equilibrium distribution which oscillates at twice the oscillation frequency. When the first release-recapture cycle is followed by a second one, the number of finally recaptured atoms depends on the phase of the oscillation and thus on the delay time between the two cycles.

In Fig. 1(b), the number of recaptured atoms is plot-

ted as a function of delay time between the two release-recapture cycles. One observes some cycles of coherent oscillation of the ensemble until the oscillation dephases mainly due to the anharmonicity of the potential. The oscillation period of 1.8 ms gives a radial oscillation frequency of 270 Hz in good agreement with the value expected for the trap parameters. The solid line in Fig. 1(b) shows the result of a Monte-Carlo simulation of the classical atom trajectories for the sequence of two release-recapture cycles with variable time delay between them.

The lifetime of atoms in the dipole trap is determined by recapturing the atoms back into the MOT after a variable storage time. For each loading and trapping cycle, three camera pictures are taken. The first picture gives the fluorescence of atoms in the MOT shortly before transfer into the dipole trap. The second one shows the fluorescence distribution after recapture into the MOT. The last picture is taken after the atoms have been released from the recapture-MOT to provide the background which is then subtracted from the first two images. The number of atoms is determined from the integral over the fluorescence image. The particle number determined by this method is estimated to be accurate within a factor of two. By normalizing the number of recaptured atoms to the number of atoms initially in the MOT, fluctuations due to variations in the initial number of atoms can be cancelled out. Variations of the particle number in the MOT, however, are found to be below 10%, so that normalization was not used in the data presented here.

The decay of the number of stored atoms is shown in Fig. 2 for the two hyperfine ground states. Even after 10 min storage time, a few hundred atoms can be detected when prepared in the $F = 3$ state. For atoms in the energetically higher $F = 4$ hyperfine ground state, inelastic binary collisions between trapped atoms lead to additional trap loss [10]. The energy of $h \times 9.2 \text{ GHz}$ released in the collisions is much larger than the trap depth, therefore both collision partners are ejected from the trap.

The decay curve for atoms in the $F = 4$ state is fitted by the solution to the differential equation $dN/dt = -\gamma N - \beta \bar{n} N$ where γ is the rate for trap loss through collisions with background gas and β is the rate coefficient for inelastic binary collisions. The fit yields a decay constant $\gamma^{-1} = 165(25) \text{ s}$. This value is consistent with the expected loss rates for collisions with background gas atoms at a pressure of 10^{-11} mbar . No indication for laser-noise induced trap loss is found. From the fit one finds a decay coefficient $\beta = 2(1) \times 10^{-11} \text{ cm}^3/\text{s}$ with the error being mainly due to the uncertainty in the absolute particle number. A previous measurement of this quantity in an opto-electric trap [11] gave a similar result.

Atoms in the energetic ground state $F = 3$ can not undergo inelastic collisions. One would therefore expect a purely exponential decay. However, the decay curve in Fig. 2 shows a faster loss of particles at higher particle numbers. It was checked that more than 95% of the

particles are initially prepared in the absolute ground state so that inelastic collisions between trapped particles can be excluded. At particle numbers below 10^4 , the decay curve approaches a pure exponential with a decay constant of $\gamma^{-1} = 140(20)$ s in agreement with the value found for atoms in the $F = 4$ state.

The faster initial trap loss can be attributed to evaporation of high-energetic atoms from the trap leading to cooling [12]. At the initial temperature, the trap depth U_0 is only about $5k_B T$. Therefore there is a certain probability that atoms leave the trap after an elastic collision. The rate for elastic collisions is given by $\bar{n}\sigma\bar{v}$ with the cross section σ and the mean relative velocity $\bar{v} = 4(k_B T/\pi m)^{1/2}$. For evaporative cooling to be effective, the ratio between the elastic collision rate (providing thermalization and evaporation) and the rate for inelastic collisions (causing losses and heating) has to be large.

Up to now, only one experiment is reported on evaporative cooling in an optical dipole trap [8]. In order to achieve sufficiently high densities, Adams *et al.* stored sodium atoms in a crossed-beam dipole trap which provides tight confinement in all three dimensions. In the simple focused-beam geometry used in our experiment it is rather surprising to find evaporative cooling since the achievable densities are rather low. The reason that evaporation actually takes place lies in the long storage times of our trap on the one hand, and the anomalously large elastic cross section of cesium at low temperatures [13] on the other hand. Although the density of cesium atoms in the dipole trap is only of the order of 10^9 atoms/cm³, one expects a thermalization time of only a few seconds due to the existence of a zero-energy resonance [14]. This time scale is indeed more than an order of magnitude smaller than the storage time.

In Fig. 3, the temperature of the trapped atoms in the $F = 3$ state is plotted versus storage time. Temperatures derived from the density distribution shown as the dots are in good agreement with measurements of ballistic expansion after release from the trap, which are shown as the three additional points in Fig. 3. One clearly observes cooling of the gas caused by evaporation of atoms from the trap at constant trap depth (*plain evaporation*). The final temperature of about $10\mu\text{K}$ corresponds to roughly $1/10$ of the potential depth. Although the temperature is reduced by roughly a factor of 2 after 150 s, the phase-space density remains almost constant since the particle number diminishes by a factor of 10 at the same time. The temperature evolution for atoms in the $F = 4$ state shows a similar behaviour, but with a slower decrease of the temperature. This is to be expected due to the faster initial density decrease through inelastic collisions and the according decrease in the rate of elastic collisions.

We apply a model developed by Luiten *et al.* [9] to simulate the temperature and particle number evolution during evaporation. Given the shape of the potential and the corresponding density of states, the model provides two coupled differential equations for the evolution

of temperature and particle number. For the true potential function of a focused Gaussian beam, the density of states diverges as the energy approaches the escape energy of the trap. We therefore approximate the trap potential by a three-dimensional Gaussian $U(\mathbf{r}) \simeq U_0 \exp(-2(x/w)^2 - 2(y/w)^2 - (z/z_R)^2)$ for which the density of states remains finite.

The potential is fully determined by the trap parameters, therefore the only adjustable parameter in the model is the rate γ for inelastic collisions with background gas and the cross section σ for elastic collisions. In the temperature range considered here, mainly s-wave collisions contribute to the cross section. The large scattering length of cesium atoms in the $F = 3$ ground state [13] results in a temperature-dependent effective cross section $\sigma(T) = \pi^2 \hbar^2 / mk_B T$ (*unitarity limit*) [14]. Note, that the cross section in the unitarity limit is completely determined by the temperature. Since the model explicitly assumes a constant cross section for elastic collisions [9], we have fixed the effective cross section to the value $\sigma = (930 a_0)^2$ ($a_0 = \text{Bohr radius}$) corresponding to a temperature of $15\mu\text{K}$.

The result of the simulation for $\gamma^{-1} = 130$ s is shown by the solid line in Fig. 3. The model prediction for the time scale of temperature decrease is in reasonable agreement with the experimental data. As can be seen from Fig. 3, however, the model slightly overestimates the rate of evaporation. This discrepancy can be explained by the influence of gravity on the one hand, and the temperature dependence of the collision cross section on the other hand. Both effects are not contained in the model, and are difficult to be included. Due to gravity, evaporation predominantly takes place in only one spatial dimension which slows down the cooling process [15]. The temperature-dependent cross section gives rise to an increased thermalization time [14] so that the rate of evaporative cooling is decreased. Nevertheless, the final temperature of the evaporation process is correctly reproduced by the model. The model also shows that the initial faster loss of particles in the $F = 3$ -state (see curve in Fig. 2) mainly stems from the evaporation process.

Employing a low-cost, off-the-shelf CO₂ laser without any longitudinal mode selection, our major concern was possible heating by laser-noise induced fluctuations of the trap potential. From the observation of evaporative cooling with a temperature decrease of about $10\mu\text{K}$ over a time scale of 100 s, one can infer that heating rates by laser noise are much lower than 100 nK/s . From the storage times of several minutes one can infer a similar upper bound for the laser-noise induced heating rates.

Due to its simple ingredients, our setup represents a minimalistic version of an optical dipole trap providing very long storage times. The universality of the QUEST opens way to experiments aiming at fundamental questions. Atomic spin states can be prepared in the QUEST with very long coherence times which is of importance for applications in quantum computing and for the search of

a permanent electric dipole moment of atoms. Another intriguing prospect is the formation and the storage of cold molecules. In the same dipole trap, we have recently also trapped lithium atoms achieving similar storage times as for cesium [4]. Currently, we are studying the properties of a simultaneously stored mixture of both species in view of sympathetic cooling and photoassociation of cold heteronuclear dimers.

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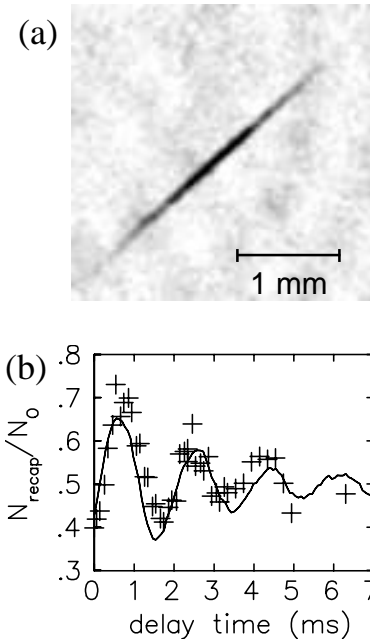


FIG. 1. (a) Distribution of cesium atoms trapped in the focus of a CO₂ laser beam. The image shows the absorption of a weak resonant probe beam. (b) Measurement of the radial oscillation frequency of cesium in the dipole trap. Two cycles of release-recapture are separated by a variable delay time. The free expansion time in each cycle is 0.7 ms. The number of recaptured atoms N_{recap} after the second cycle is normalized to the number of atoms after the first cycle N_0 . The number of recaptured atoms oscillates at twice the radial oscillation frequency. The result of a Monte-Carlo simulation is depicted by the solid line.

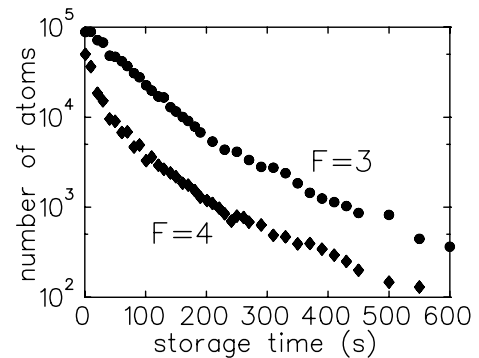


FIG. 2. Evolution of the number of trapped cesium atoms as a function of storage time. The atoms are initially prepared in either the $F = 3$ or $F = 4$ hyperfine ground state.

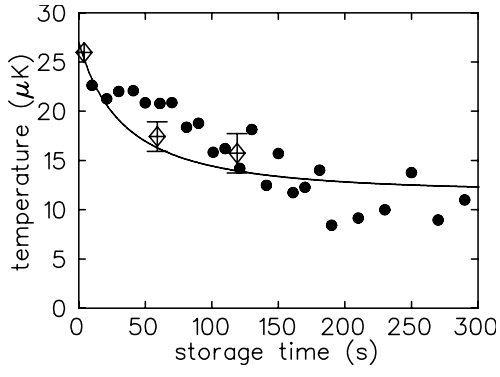


FIG. 3. Evaporative cooling of the trapped cesium gas. The dots give the temperature derived from the axial extension of the trapped atom cloud while the diamonds show the result of a ballistic expansion measurement. The solid line depicts a simulation of plain evaporative cooling in the trap.